UCRL-2335

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UNIVERSITY OF CALIFORNIA

Radiation Laboratory

Contract No. W-7405-eng-48

EVIDENCE FOR SUBSHELL AT Z = 96

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September 3, 1953

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The evidence is decisive that major nuclear shells are completed at 82 protons and 126 neutrons (both represented by the nuclide Pb^{208}) and these, along with major shells at 82 neutrons and certain lower nucleon numbers (N or Z = 20, 28, 50), are well explained by the strong spin orbit coupling model of Mayer[1] and Haxel, Jensen, and Suess.[2] This model suggests the filling of quantum states at certain intermediate points, and there is an accumulating amount of evidence that such "subshells" are also discernible, for example, at Z = 58[3,4,5] and Z = 64.[6,7]

The evidence from alpha radioactivity, both (1) the effect of the nuclear radius shrinkage on the relationship between energy and half-life and (2) the discontinuities in the plots of energy vs. mass number at constant Z, gives a striking indication[8] of the closing of major shells at Z = 82 and N = 126. Application of these sensitive criteria as tests for the much smaller "subshell" effects in the regions Z > 82 and N > 126 leads to some evidence for such a subshell at Z = 96 (curium).

Since it has been shown that the Gamow-Gurney-Condon type of formula for alpha decay applies very well to the ground state to ground state transition for even-even alpha emitters,[8] the known[9] alpha energies and partial half-lives were used in the Preston[10] form of the formula to calculate the nuclear radii of a number of even-even nuclides in the range Z = ~~90~~ 94 to ~~96~~ 98. Using these radii a value of r_o was calculated for each nuclide from the relationship radius = $r_o A^{1/3}$ and the plot in Fig. 1 of the average value of r_o (r_o generally decreasing with increasing Z) for each element indicates a just discernible minimum or plateau at Z = 96. The average value of r_o for each element was plotted because there is no discernible regular variation of r_o with A at constant Z.

The stable shell of 82 protons is attained upon completion of the $h_{11/2}$ level and the spin of Bi^{209} (9/2) indicates that the 83rd proton begins the filling of the $h_{9/2}$ level as might be expected. However, if the $h_{9/2}$ level is raised in energy as more protons are added, so that the $f_{7/2}$ and $f_{5/2}$ are filled before the $h_{9/2}$ levels, one might expect subshell effects at Z = 90 and 96. If the quantum states are filled in this order, the variation of r_o with Z should perhaps also indicate an effect Z = 90. A careful consideration of the values of r_o in the region on both sides of Z = 90 points to a barely discernible plateau in the variation of r_o with Z at this atomic number.

In the case of Z = 96 there is an additional argument which points to the completion of a subshell here. The known odd-even isotopes of berkelium, Bk^{243} and Bk^{245}, are highly "hindered"[8] in their most prominent modes of alpha decay, i.e., they decay much slower than the simple formula would indicate. This exceptional degree of hindrance is not observed for similar (odd-even) isotopes of any other odd Z alpha particle emitter with the exception of bismuth (Z = 83) where the slowed rates of decay are presumably to be associated with the closed proton shell (and consequent shrunken radius) at Z = 82.

There are other lines of evidence which may also point to the filling of the $f_{7/2}$ and $f_{5/2}$ before the $h_{9/2}$ proton states. The spins of Np^{237} [11] and Am^{241} [12] are both 5/2 as expected on this basis. On the other hand, the spins of Ac^{227} [13] and Pa^{231} [14] have both been reported as 3/2 indicating perhaps that the odd proton occupies the $p_{3/2}$ state, whereas spins of 7/2 and 5/2 corresponding to $f_{7/2}$ and $f_{5/2}$ states, respectively, would be expected. Whether or not this indicates a breakdown of the single particle model it does seem to indicate that arguments based on spin values cannot be conclusive here. It is interesting to add that a consideration of the systematics of beta radioactivity in this region also leads to the assignment of spectroscopic states in agreement with the suggested higher position of the $h_{9/2}$ level energetically.

It is interesting to note that arguments based on spin values[15] indicate that in the case of neutrons the $f_{7/2}$ level fills before the $h_{9/2}$ level just after the completion of the major shell at 82 neutrons. Thus, the situation is analogous to that postulated for protons although the evidence is not clear on the relative position of the $f_{5/2}$ and $h_{9/2}$ neutron levels.

It seems likely that in the region following the major closed shell at 126 neutrons, which is completed with the filling of the $i_{13/2}$ states, the $i_{11/2}$ level is not occupied until the $g_{9/2}$ and possibly also the $g_{7/2}$ and $d_{5/2}$, etc., states are filled. Attempts to apply the above mentioned criteria of alpha decay data do not lead to any discernible evidence for subshells up to N = 148. Successful application of these criteria here probably awaits both a larger quantity of and more accurate alpha decay data in this region. There is only one spin value known in this region, that of U^{235}, which has been reported as 5/2 or 7/2 with the former value the more probable.[16] Since U^{235} has 143 neutrons either spin value would fit nicely with the view that the $i_{11/2}$ lies above the $g_{9/2}$, $g_{7/2}$, and $d_{5/2}$ levels.

The generous help of F. Asaro and D. C. Dunlavey in making numerous calculations is gratefully acknowledged.

FIGURE CAPTION

Figure 1. Plot of average values of r_o vs. Z. Following isotopes included: Po^{212}, Po^{214}, Po^{216}, Po^{218} for Po; Em^{220}, Em^{222} for Em; Ra^{222}, Ra^{224}, Ra^{226} for Ra; Th^{226}, Th^{228}, Th^{230}, Th^{232} for Th; U^{230}, U^{232}, U^{234}, U^{236}, U^{238} for U; Pu^{236}, Pu^{238}, Pu^{240}, Pu^{242} for Pu; Cm^{242}, Cm^{244} for Cm; Cf^{246}, Cf^{248} for Cf.

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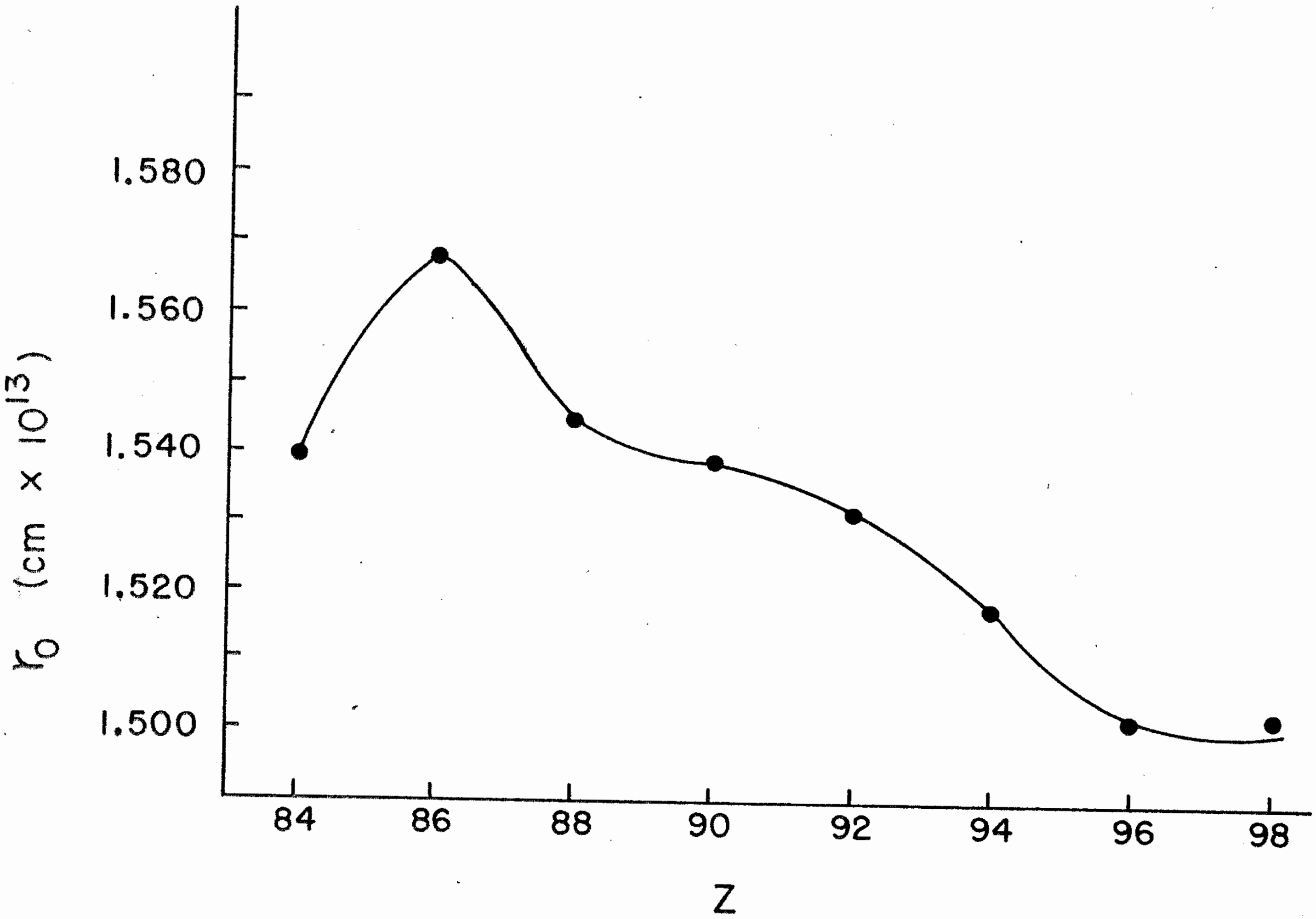

1.580
1.560
1.540
1.520
1.500
r_0 (cm x 10^{13})
84
86
88
90
92
94
96
98
Z